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Wet torrefaction of forest residues

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Abstract

Wet torrefaction of forest residues, which is one of the cheap and most abundant biomass resources in Norway, was experimentally studied. Freshly cut branches of Norway birch and spruce were used as feedstock, without and with pre-drying to simulate the drying during fuel storage prior to torrefaction. The results show that both torrefaction temperature and holding time have significant effects on the solid yield and its fuel properties. Increases in heating value of up to 11.4–11.6% and reductions of specific grinding energy of 13.3–16.0 times could be achieved via wet torrefaction. Torrefied forest residues have lower ash contents compared with the raw materials. Pre-drying and especially the drying methods have significant effects on the solid yield.

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1. Introduction

Dry torrefaction (DT), which may be defined as thermal treatment of biomass in an inert environment at atmospheric pressure and temperatures within the range of 200–300°C [1, 2], is a promising pretreatment method to convert a wide range of biomass to energy dense solid fuel with much better grindability and increased heating value compared with the raw biomass [1–3]. The technology has been developed rapidly and is ready for market introduction and commercial operation [4]. However, it has been claimed that no clear winner in this area can be identified so far. This situation might partially be due to the fact that current DT technologies use wood chips from stem wood, a feedstock of relatively high quality and thus cost. Utilization of inexpensive biomass recourses such as agricultural residues, forest residues and other biomass wastes may help reducing the total cost of biomass torrefaction at

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industrial scales. However, the typical higher moisture contents of these biomass type make DT challenging. Wet torrefaction (WT), which may be defined as treatment of biomass in a hydrothermal media (HM) or hot compressed water (HCW) at temperatures within 180–260°C [5, 6], has therefore also been developed to overcome this challenge.

Our recent study [5] on WT of wood fuels has demonstrated advantages of WT over DT for upgrading biomass solid fuels. This present work continues the study, moving closer to the industrial conditions by using forest residues as feedstock for WT.

2. Materials and methods

Wet and freshly cut branches with diameter of 2–2.5 cm from Norway spruce and birch were collected from a local forest in Trondheim, Norway. The moisture contents of the feedstocks (determined by the standard method ASTM D4442-07) were $49.96 \pm 2.34\%$ and $56.31 \pm 1.93\%$ for the spruce and birch samples, respectively. Prior to WT experiments, the branches were cut into slices with a thickness of 3–4 mm and the bark was completely removed to avoid possible interference caused by impurities/contaminants and composition differences. For a comparison with WT of wood from our previous study [5], the collected branches were pre-dried at $103 \pm 2^\circ\text{C}$ in a muffle furnace for 48h prior to WT. The common WT conditions, procedure and assessment methods described in our previous study [5] were adopted for this present work. It was at 70 bar and three temperatures (175, 200, 225°C), and for three holding times (10, 30, 60 min).

3. Results

3.1. Effects torrefaction temperature and holding time on the solid yield



Fig. 1. Effects of temperature on the solid product yield of spruce (A) and birch (B) branches

Fig. 1 presents the effect of WT temperature on the solid yield of spruce and birch branches torrefied at 70 bar and different temperatures (175, 200, 225°C) for 30 min. Data from WT of spruce and birch wood in the identical conditions as reported in our previous work [5] were also included for comparison. As can be seen from Fig. 1, when the torrefaction temperature is increased, the solid yield is decreased for all the feedstocks. However, among the feedstocks, the wood cubes have the highest solid yields and the dried branches have the lowest solid yields. When the temperature is increased from 175 to 225°C the solid yield decreases from 82.0 to 67.6% and from 72.2 to 62.1% for wet and dried spruce branches, respectively; and from 78.5 to 56.9% and from 74.1 to 52.7% for wet and dried birch branches, respectively. The differences in solid yields are less significant when increasing the temperature for spruce (Fig. 1A) compared to birch (Fig. 1B). The effect of holding time shows similar trends but is less pronounced than the effect of temperature.

3.2. Effects on fuel properties of the solid product

The proximate analyses and higher heating values (HHV) of the solids obtained from WT of freshly cut forest residues at different temperatures and holding times are presented in Table 1. Increasing torrefaction temperature or holding time enhances the fixed-carbon content and thus the heating value but decreases the volatile matter content in the torrefied solid fuel. Comparing with the untreated materials, the increase in fixed-carbon content is from 20.6 to 74.5% for the torrefied spruce and 16.9 to 104.4% for the torrefied birch, when increasing the treatment severity. Moreover, increases in HHV vary from 3.3 to 11.6% for the torrefied spruce and from 1.9 to 11.4% for the torrefied birch within the range of tested conditions. Table 1 also reveals that the ash contents of most solids obtained from WT of branches are lower than that of the corresponding raw materials, which results from the leaching effect during WT.

Table 1. Proximate analysis and higher heating values of raw and torrefied forest residues

Torrefaction condition	Spruce				Birch			
	Ash ^a	VM ^a	FC ^a	HHV ^b	Ash ^a	VM ^a	FC ^a	HHV ^b
Raw	0.68	85.18	14.14	19.80	0.64	89.74	9.63	18.84
175°C–30min	0.54	82.40	17.06	20.45	0.56	88.19	11.25	19.20
200°C–10min	0.58	81.61	17.81	20.60	0.61	86.66	12.73	19.51
200°C–30min	0.52	80.76	18.72	20.80	0.55	83.40	16.04	20.23
200°C–60min	0.46	76.04	23.50	21.84	0.61	81.63	17.76	20.58
225°C–30min	0.50	74.82	24.68	22.08	0.65	79.67	19.68	20.99

^awt %, dry basis. ^bMJ/kg, dry basis

The specific grinding energy (SGE) and moisture uptake level of raw and wet-torrefied branches are presented in Fig. 2. Again, the common conditions for WT were 70 bar as pressure and 30 minutes as holding time. It can be seen from Fig. 2A that increasing WT temperature decreases significantly the SGE of the torrefied forest residues. The highest reduction in SGE is 13.3 and 16.0 times for spruce and birch torrefied at 225°C, respectively. The moisture uptake level also decreases after WT, as shown in Fig. 2B, the torrefied samples uptake less moisture when treated at higher temperatures. All tested samples reached the equilibrium moisture content (EMC) within two days. Spruce and birch torrefied at 225°C and for 30 minutes have respectively an EMC of 8.6% and 8.9% compared with 21.4% and 20.3% for the untreated branches. It indicates a much improved hydrophobicity of the torrefied fuels compared with the raw fuels. The effects of holding time on the grindability and hydrophobicity are similar but less pronounced compared with the effect of temperature.



Fig. 2. The specific grinding energy (A) and moisture uptake level (B) of forest residues torrefied at different temperatures

4. Discussion

The fact that WT of the wet branches gave lower solid yields than the pre-dried branches is somehow not as expected. It was suspected that this may be caused by the relatively hot and rapid drying at $103 \pm 2^\circ\text{C}$, which might have resulted in cracks or distortions in the biomass structure [7, 8]. Therefore, extra

experiments were carried out using naturally dried spruce branches to check the suspicion and see if the structure disturbance effect of the forced drying is significant. For this, the branches were allowed to dry naturally at room temperature under a continuous air flow until a constant level of the moisture content (6.72%) was established. The data presented in Fig. 1 show that the solid yield of WT at 70 bar, 200°C, and for 30 minutes is decreasing (75.3, 73.6 and 67.3%) for the naturally dried, fresh and oven-dried feedstocks, respectively. This investigation has confirmed the suspicion and helps explain the unexpected observation.

In addition, WT of the tree branches produces less solid product, compared with WT of the wood in the same conditions. It is probably due to the lower fixed carbon content, weaker structure [9] and higher ash content of the branches compared with the wood. On the other hand, the improvements in fuel property of forest residues via WT are in line with those of wood reported in our previous work [5] and in literature [6, 10].

5. Conclusion

WT of Norwegian forest residues, spruce and birch branches, was carried out. The effects of WT conditions on the yield and fuel properties of the solid product were experimentally investigated. The results show the effect trends similar to that observed from for WT of spruce and birch stem woods. Either increasing torrefaction temperature or holding time decreases the solid product yield, but enhances the fuel properties of the product. Birch branches are more reactive than spruce branches in the same WT conditions. However, WT of forest residues produces less solid product, compared with WT of stem wood in the same conditions.

Forced pre-drying of forest residues accelerates the WT process, whereas natural pre-drying has an opposite effect. Increases in heating value of up to 11.4-11.6% and reductions of specific grinding energy of 13.3-16.0 times could be achieved via WT. In addition, the ash contents of forest residues can be significantly reduced via WT.

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7. References

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